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Geometry Modeling and Grid Generation for "Icing Effects" and "Ice Accretion" Simulations on Airfoils

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Abstract

There are two distinct icing-related problems for airfoils that can be simulated. One is predicting the effects of ice on the aerodynamic performance of airfoils when ice geometry is known ("icing effects" study). The other is simulating ice accretion under specified icing conditions ("ice accretion" simulation). This paper will address development of two different software packages for two-dimensional geometry preparation and grid generation for both "icing effects" and "ice accretion" studies.

Introduction

Simulation of aircraft icing presents challenging problems for Computational Fluid Dynamics (CFD) due to irregular ice shapes with varying degrees of surface roughness and resulting complex flow phenomena. Quality grids are required to obtain viscous flow solutions around iced airfoils sufficiently accurate to provide insights to flow phenomena and airfoil performance degradation. Unfortunately, grid generation for iced airfoils presents considerable difficulty because most ice shapes are highly irregular with sharp corners and segments with very high curvature (Figure 1). In addition to geometric complexity, the flow can be complex as it separates in the region aft of prominent ice shapes, even for moderate angles of attack. Thus, geometry

preparation and grid-generation for icing problems are currently difficult and time-consuming.

An "icing effects" study was performed for ice shapes provided by the NASA Glenn Icing Research Tunnel (IRT). The approaches employed in this analytical study and its results were reported previously [1] [2]. The highly irregular ice shapes, with varying degrees of roughness, are first smoothed in a controlled manner using the control point formula [3], multi-block structured grids are then generated [4], and finally Navier-Stokes flow simulations are performed using the flow solver WIND [5]. This study suggests that an efficient and robust ice-geometry preparation and grid generation tool kit is needed for more challenging ice shapes in order to perform routine "icing effects" studies. In response to this need, a software toolkit, called "SmaggIce" [6, 7], is being developed for icing effects studies. Although automation will be attempted wherever possible, the primary mode of operation for SmaggIce will be interactive in order to handle the multitude of ice shapes that are routinely encountered in aircraft icing problems. Figures 1, 2(a), 3(a), and 4 show some of the ice shapes that are regularly encountered in CFD icing simulations. Being customized for iced airfoils, this code employs ice-shape preparation using control points, and block topologies that are appropriate for most ice shapes obtained by experiments and from the "LEWICE" [8] ice accretion prediction code. At the completion of development, SmaggIce will facilitate a seamless interactive process from geometry preparation to Navier-Stokes (NS) flow simulation.

Another problem relevant to aircraft icing is the use of CFD as a component of the ice accretion prediction process. Currently, the rate of ice accretion is estimated from water droplet trajectory and collection efficiency calculations that are based on a potential flow calculation. However, for single-element airfoil simulations at high angles of attack and multi-element airfoil simulations in landing configuration, a NS flow simulation is needed for accurate prediction of the resulting ice shapes. However, since ice accretion is predicted in increments of time, the geometric modeling, grid generation, and flow simulation components of the ice accretion prediction process need to be automatic and robust to reduce the overall simulation time. An integrated software package, "ICEG2D" [9], for automated prediction of flow fields for ice accretion prediction is being developed for this purpose. In the first phase, the automatic integrated geometry/structured grid/flow simulation software system for single-element airfoils has been completed. It is being extended to include generalized grid generation/solution capability [10] including adaptation and refinement.

Geometry Modeling and Grid Generation for "Icing Effects" Study

During the development of "SmaggIce," the value of each technology component is being assessed in light of its contribution to the entire process. The complete icing effect simulation includes surface preparation, domain decomposition, grid generation, and NS flow simulation. As for the grid topology, a blocked structured grid is chosen because it provides accurate viscous solutions. The relatively large amounts of time and labor required for the structured grid generation can be overcome if the geometry preparation, grid generation, and flow solution processes can be performed efficiently in an interactive manner. A previous study indicated that a structured grid CFD solver such as WIND predicted flow fields with reasonable accuracy considering the complexity of the ice geometry [2].

The SmaggIce software tool kit is being developed in two planned phases. Version 1, developed in the first phase, was released in February 2000. It provides interactive ice shape probing (Figure 2) and interactive ice surface preparation for grid generation (Figure 3). Figure 2(a) illustrates measurements of ice shape characteristics that affect aerodynamic performance. SmaggIce allows the user to save the image displayed in the graphics window in a variety of formats. Figure 2(b) shows the measured data, generated by SmaggIce, that include upper and lower icing limit locations, the arc length between them, and height and angle of a horn. These measured data can also be saved in a file for a later use. Figure 3(a) shows an ice geometry with many sharp corners while 3(b) illustrates controlled smoothing performed using control points as a preparation for grid generation.

An interactive-automatic blocking concept is now being investigated to decompose the flow domain into a class of built-in block structures depending on the ice shape. Structured grids are generated in each block using transfinite interpolation and then smoothed by an elliptic smoother for improved grid quality. This process is being tested in a technology demonstration code, SMG2D-ICE [11]. Its relevant technologies will be integrated into SmaggIce. Figure 4 shows an example of the multi-block topology for a complex ice shape with horns and cavities. The use of the multi-block grid for NS flow analysis sometimes introduces unnecessary grid clustering along in-field block boundaries due to the high curvatures around horn tips and in cavities. The use of a NS grid layer around the iced airfoil allows quality grid generation possible for a broad range of ice shapes. Quality NS grids can be generated using this approach as illustrated in Figure 5.

SmaggIce version 2 will include domain decomposition, grid generation, and grid quality check and control. It will be closely tied with the flow solver WIND [5] and will be capable of simulating the entire process. Figure 6 shows a flow diagram of version 2, which will have several unique features. These features include determining ice-shape classes, selecting critical points such as horn tips and icing limits that will be used in domain decomposition (Figure 4), defining/redefining block topology, and a direct link to WIND using the CFD General Notations Systems (CGNS) standard [12].

Surface Preparation and Grid Generation for "Ice Accretion" Prediction

The NS flow solution offers potential to improve the prediction of water droplet trajectories as the angle of attack increases. However, it will only be useful if the grid generation and subsequent NS simulation are automated and robust since the ice accretion prediction process typically requires many cycles. For instance, if the ice growth model uses a 30 second time increment, then the 10-minute ice accretion prediction requires 20 ice-accretion cycles, and thus 20 grid generation/solution cycles.

In ICEG2D, automatic distribution of points on a NURBS representation of the iced airfoil surface is accomplished using an equidistribution algorithm in the iced region (with the weight function based on surface curvature) and algebraic stretching for the remainder of the airfoil. A parabolic marching scheme is used to generate the grid in layers. The parabolic formulation eliminates the difficult task of specifying points on the outer boundary of the grid. Furthermore, the Poisson equations used in the parabolic scheme allow inclusion of the functions needed for effective control of grid point spacing. Both single- and double-block C-type, structured grids can be generated automatically. For the double-block grid, the inner block surrounds the near field of the iced airfoil while the outer block overlaps with the former. ICEG2D automatically generates the files necessary to perform a flow simulation using the general purpose flow solver NPARC.

Currently, the generalized grid capability is being incorporated into ICEG2D. The same parabolic grid generation algorithm is used to generate the grid in layers. However, at the interface between layers, point insertion or deletion can be performed based on prescribed geometric or flow gradient constraints. We have termed these grids semistructured, generalized grids [10]. Sample grids generated automatically using the parabolic marching scheme for structured and semistructured grids are shown in Figures 7 and 8 respectively. HYB2D [13] is the flow solver currently being considered for incorporation into ICEG2D.

Concluding Remarks

In order to carry out two distinct icing related tasks for airfoils in a routine fashion, two separate software packages (SmaggIce and ICEG2D) are being developed. SmaggIce is being developed for the simulation of "icing effects" on airfoil aerodynamic performance, and ICEG2D is being developed for ice accretion simulations. In order to handle most of the infinite variations of ice shapes that aircraft icing encounter, SmaggIce will provide interactive capability as its primary mode of operation for surface examination/preparation, domain decomposition, grid generation, and preparing and submitting a WIND job. On the other hand, ICEG2D is being automated since ice-accretion simulation requires many cycles of geometry modeling/grid generation/flow simulations.

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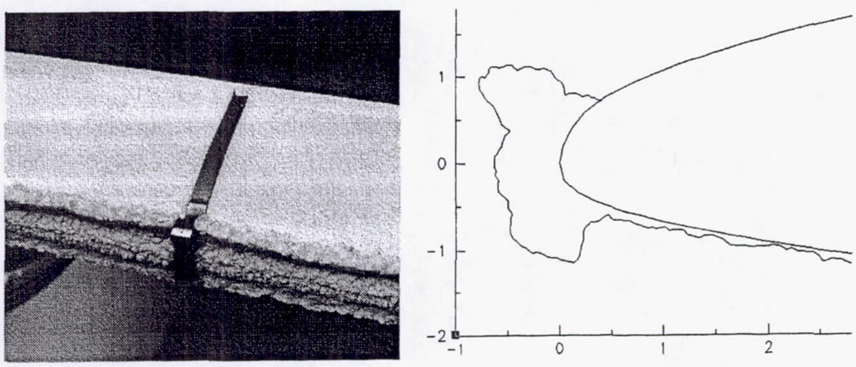
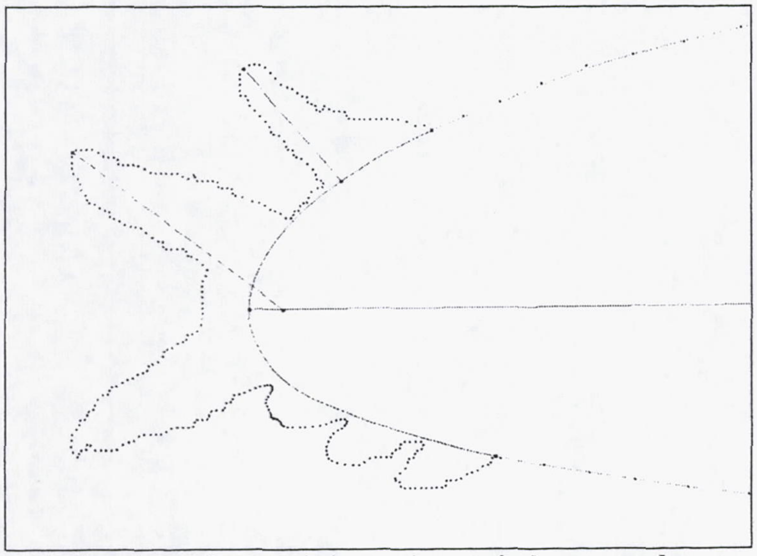
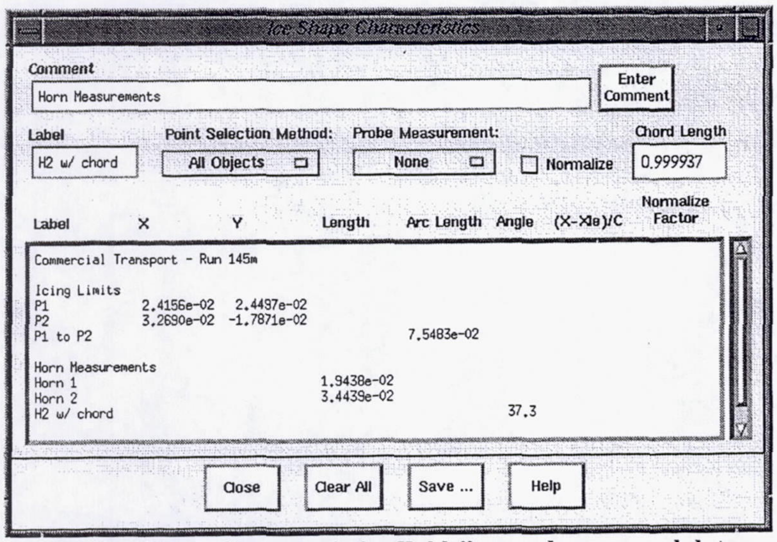


(a) Casting of Actual Ice on a Wing **(b) Sample 2D Ice Shape**

Figure 1. Sample 3D and 2D Ice Shapes

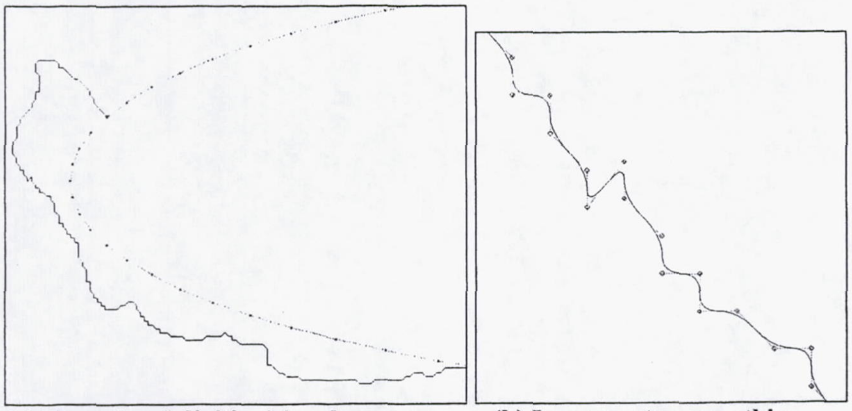


(a) Ice shape characteristics are interactively measured.



(b) "Ice Shape Characteristics Table" records measured data

Figure 2. Interactive measurement of ice shape characteristics



(a) Traced and digitized ice shape (b) Ice geometry smoothing

Figure 3. Surface preparation for grid generation

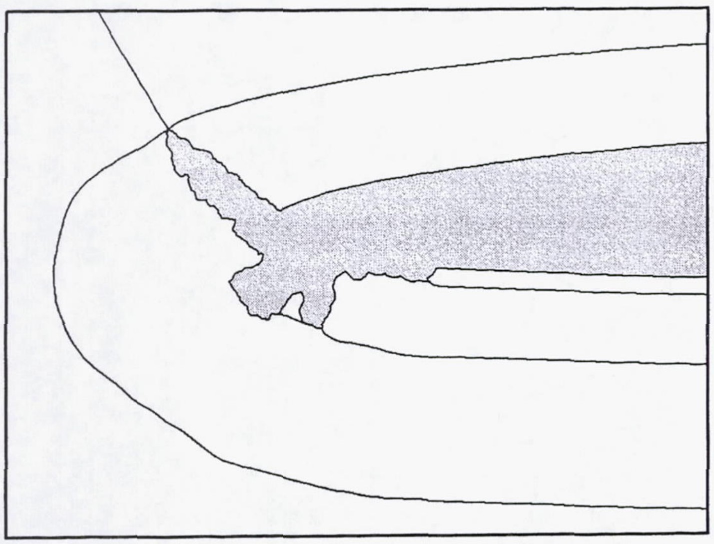


Figure 4. Multi-block Topology for a Complex Ice Shape

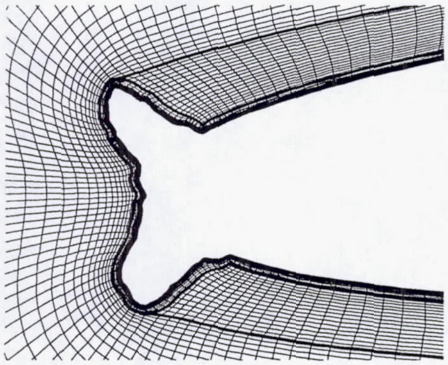


Figure 5. Multi-block Grid with NS Grid Layer (4 Blocks)

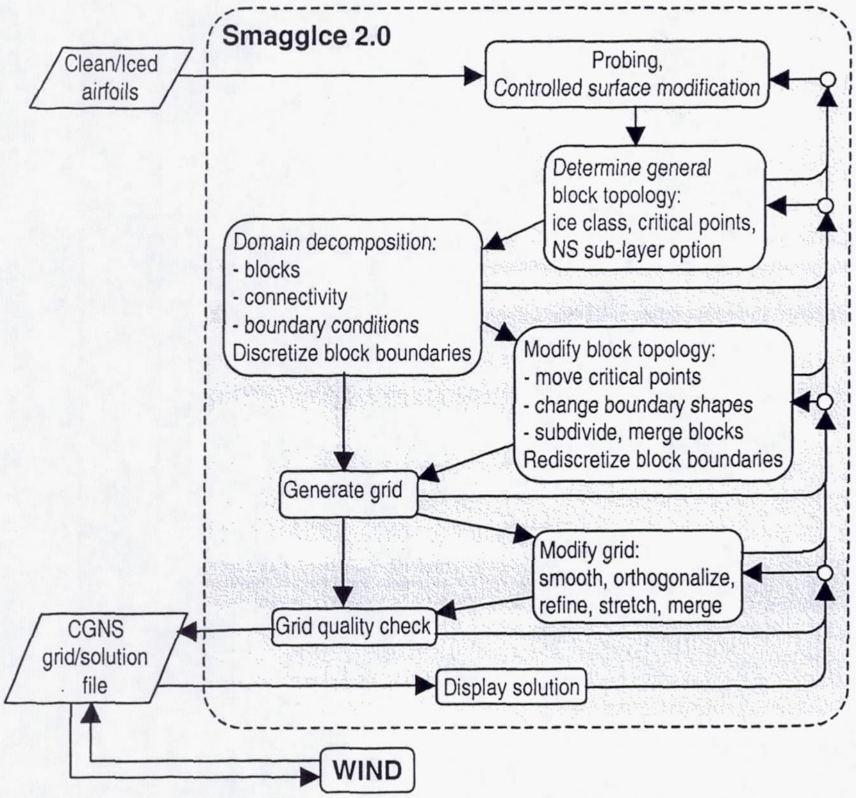


Figure 6. SmaggIce Version 2 Flow Diagram

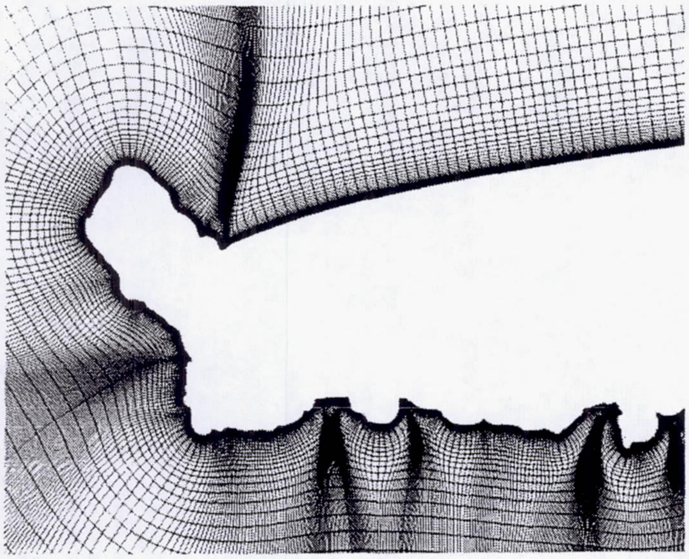


Figure 7. Fully Structured Grid for Airfoil with Ice Accretion

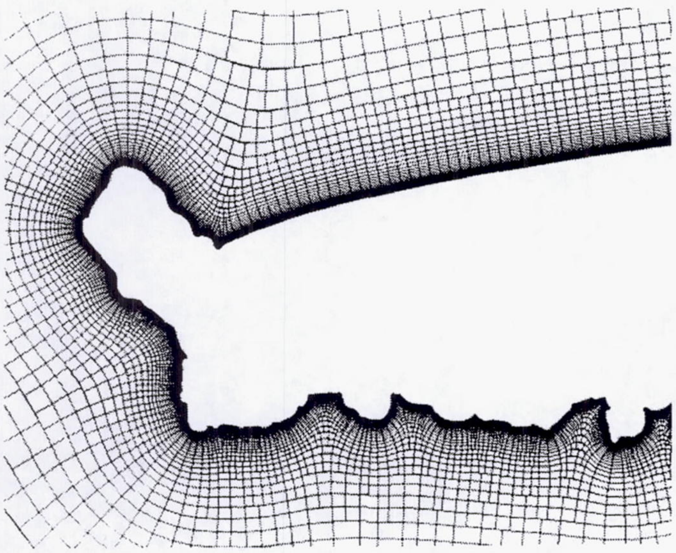


Figure 8. Generalized Grid for Airfoil with Ice Accretion